SECTION I.—AEROLOGY.

SECTION II.—GENERAL METEOROLOGY.

THE SNOWFALL OF THE EASTERN UNITED STATES.[1]

By CHARLES FRANKLIN BROOKS.

[Dated: U. S. Bureau of Plant Industry, Washington, Dec. 15, 1914.]

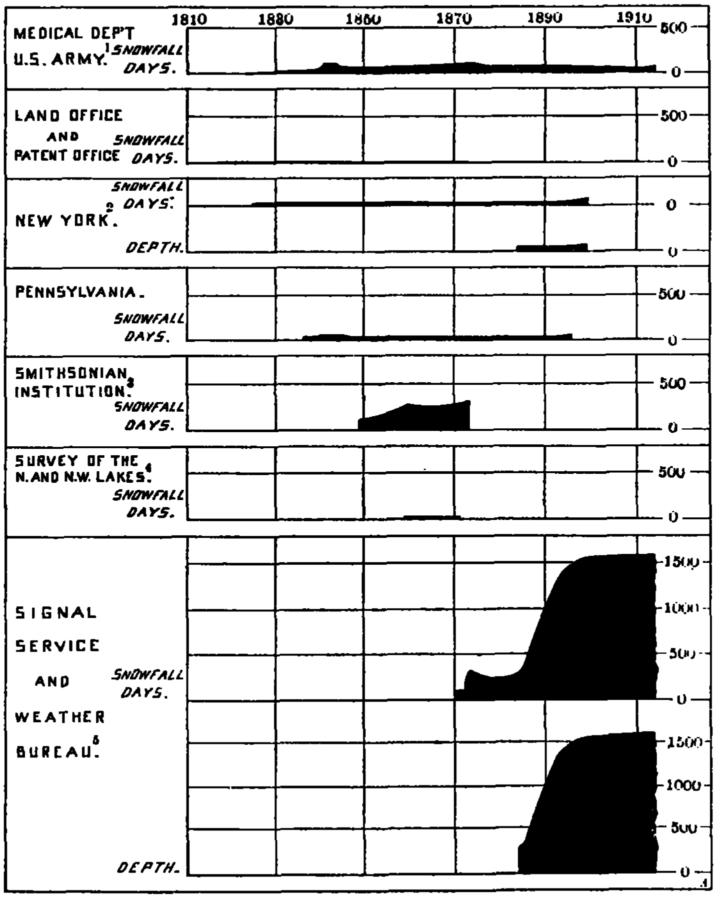
INTRODUCTION.

SNOWFALL OBSERVATIONS.

The earliest observations of snowfall in the United States were made by independent observers. These records are to be found in their original journals and scattered through newspapers, almanacs, books on climate, storms, or travels. Great snowstorms have always received attention. Sidney Perley has collected the reports of many such in his "Historic Storms of New England" (Salem, 1891), the delight of the advocate of the "old-fashioned snowstorm" (1).

As regards more or less continuous records, some observers have merely recorded the days on which snow occurred; others have, in addition, from time to time mentioned the approximate depth of snowfall and snow water, and still others have made complete snowfall observations. The manuscript Meteorological Journal of Gov. William Plummer, Epping, N. H., 1796 to 1834, in the library of Blue Hill Observatory, not only contains full snowfall records day by day, but also has them neatly summarized for the whole period (2). The American Almanac from 1834 to 1861 published the results of meteorological observations at several places, many of the series containing snowfall records. Blodget has summarized some of these and others; they are given in his "Climatology of the United States" (see p. 3).

Organized meteorological observations, including snowfall days, began in 1814, when the Army post surgeons were ordered to keep weather diaries. However, few returns are to be had for the ensuing five years. In 1817 Josiah Meigs, Commissioner of the General Land Office, started meteorological observations at the 20 land offices in the eastern United States. Observations of snowfall days and snowstorms were included. In 1819 Surg. Gen. Lovell organized meteorological observations in the United States Army on a firm basis. In 1825 the New York Legislature established the "New York University system" of meteorological observations. Snowfall days were regularly recorded and depth of snowfall received some attention. In 1836 Pennsylvania began a State weather service, the reports going to Prof. J. P. Espy, of the Franklin Institute (3). In 1840 J. P. Espy, on taking charge of the Army meteorological observations, succeeded in procuring the services of more than 100 voluntary observers. He, with Loomis and Redfield, encouraged Joseph Henry, then Secretary of the Smithsonian Institution, in the establishment of a weather service national in scope. Such a service went into operation in 1849. The Patent Office observers (outgrowth of Meigs's system), the observers of the State services, and many other voluntary observers sent meteorological reports as a part of the Smithsonian system. Melted snowfall was recorded as distinct from rain (4). From 1859 to 1871 the Survey of the Northern and Northwestern Lakes, under the Engineer Corps of the United States Army, observed snowfall days among other meteorological phenomena.



[1] Army Meteorological Register, 1826, 1840, 1851, 1855, 1860. (Appendix to the Statistical Report on the Sickness and Mortality in the Army of the United States from 1855–1860, by R. H. Coolidge.)

[2] Regularly published in the annual reports of the Regents of the University of the State of New York, 1825–1849, and for a few stations later. See also F. B. Hough, New York Meteorology, 1826–1850, and 1851–1863.

[3] Original manuscripts in the archives of the Weather Bureau.

[4] Annual Report on the Survey of the Northern and Northwestern Lakes for the year ending June 30, 1867, by W. F. Raynolds, Appendix U, Report of Secretary of War, 2d sess., 40th Cong.; vol. 2, 1867–68.

[5] See figure 2 below.

FIG. 1.—Graphic representation of the history of organized snowfall observations in the eastern United States. (Right-hand scale indicates number of stations reporting.)

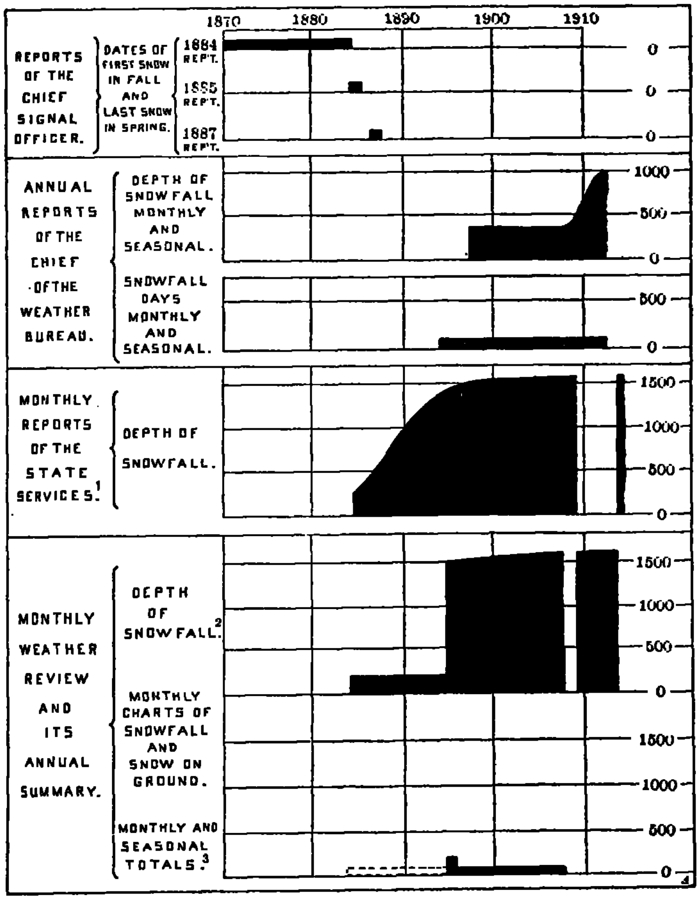
In 1870 Congress authorized the meteorological division of the Signal Service. In 1873 this new bureau took over the preceding records from the Army surgeons, and in the same year the Smithsonian Institution transferred its meteorological work to the Signal Service. Extensive observations of the depth of snowfall for each 24 hours began in the spring of 1884. "The number of inches and tenths of inches of snow which fell during the 24 hours was determined as accurately as possible by

[1] This work is the revised major portion of a thesis submitted as part of the requirements for the degree of doctor of philosophy in meteorology at Harvard University. It was prepared from June, 1913, to May, 1914, under the supervision of Prof. Robert DeC. Ward.

The section on "The Distribution of Snowfall in Cyclones of the Eastern United States" was published in the MONTHLY WEATHER REVIEW, June, 1914, 42: 318–330.—*The Author.*

measurements made at points where the snow appeared to be of average depth" (5). In 1891 the meteorological work of the Army Signal Service was transferred to the Department of Agriculture and the present Weather Bureau was organized (6).

Figure 1 represents graphically the history of organized snowfall observations in the United States east of the Mississippi River, and figure 2 shows the history of the



[1] Organized into the Climate and Crop Service, 1895–1899.
[2] 1884–1894, only the snowfalls of 10 inches or more were generally given.
[3] Summary 1884–1895 in the Annual Summary of the Monthly Weather Review for 1895.

FIG. 2.—Graphic representation of the history of publication of snowfall data by the U. S. Signal Service and the U. S. Weather Bureau. (Right-hand scale indicates number of stations reporting.)

publication of snowfall data by the Signal Service and Weather Bureau.

SNOWFALL DISCUSSIONS.

Perhaps the earliest discussion of the snowfall of the eastern United States is in C. F. Volney's, "A View of the Soil and Climate of the United States of America" (7). From 1795 to 1798 Volney was traveling in this country, and during that time gathered the information presented. The heavy snowfall of northern New England and eastern Canada is mentioned in marked contrast to the snowfall of equal latitudes in Europe. Southward the snowfall decreases rapidly. Virginia is described as practically the southern limit of sleighing; the distribution of sleighs seen in barnyards indicates this. In the Appalachians the snow goes much farther south.

Two extraordinary snowstorms are mentioned: At Norfolk, Volney says that 5 feet of snow fell on February 4, 1798, and 40 inches more with a northeast wind during the night February 14. Most of the snow in the eastern United States is said to come with northeast winds. The influence of available moisture as a considerable factor in snowfall was recognized; Volney says that Quebec has more snow than Montreal because it is not so far from the Atlantic. The Ohio Valley and the lee shores of the Great Lakes have wet northwest winds in winter because of the moist surfaces traversed.

Dr. Samuel Forry in his "Climate of the United States and its Endemic Influences" (New York, 1842), and "Meteorology" (New World, New York, April, 1843), touches on snowfall in a general way. He mentions the well-known protection which a snow cover, as a poor conductor of heat, affords vegetation. In discussing alleged changes of climate in this country two of his quotations relate to snowfall. He quotes Richard Sexton as follows:

> But there will doubtless be an amelioration in this particular [climate] when Canada and the United States shall become thickly peopled and generally cultivated. In this latitude then like the same parallels in Europe at present, snow and ice will become rare phenomena. * * *

He also quotes from Thomas Jefferson's Notes on Virginia:

> Snows are less frequent and less deep; they do not lie below the mountains more than one, two, or three days and very rarely a week. They are remembered to have been formerly frequent, deep, and of long continuance. The elderly inform me that the earth used to be covered with snow about three months in every year.

Such statements Forry justly claims are disproved by records.

Lorin Blodget devoted two pages to snowfall in his voluminous "Climatology of the United States" (8). He uses data gleaned principally from the American Almanac, and the Army's and States' observations. He mentions the usual transiency of snow south of the Great Lakes as compared with the 2 feet or more of snow which stays on the ground for several months in northern New England, northern New York, and eastern Canada. Blodget remarks on the great variation of snowfall from year to year. In New York there are prodigious amounts sometimes; in the winter of 1855–56, in one storm 3 to 5 feet of snow fell on the plain of western and central New York, and still more in the mountains east and south. Other winters may pass with relatively little snowfall. Westward the snowfall generally decreases. However, in the vicinity of Lake Superior the snowfall is heavy, but less than the extremes of New York.

> Below or south of the 41st parallel the snows are extremely irregular and yet often profuse and excessive. They are more likely to occur in February and the spring months as extraordinary phenomena than in the early part of the winter, and instances are frequent of profuse April snows. A few citations of the observed average depths of snow may be given here [Table 1], taken from various published notices mainly (p. 345).

TABLE 1.—*Observed average depths of snowfall at various periods and from various sources.*

Sources.	Blodget's table. 1		During next 50 years. 2		Difference.
Locality.	Record.	Depth.	Record.	Depth.	1—2
	Years.	*Inches.*	*Years.*	*Inches.*	*Inches.*
Oxford County, Me	12	90	14	85	+ 5
Dover, N. H	10	68.6			
Montreal, Canada	10	67	15	125.7	−58.7
Burlington, Vt	10	85	18	61	+24
Worcester, Mass	12	55	18	51	+ 4
Do.[1]	21	53.5			2.5
Amherst, Mass	7	54	18	46	+ 8
Hartford, Conn	24	43	18	45	− 2
Lambertville, N. J	8	25.5	17	34.5	− 9
Cincinnati (Dr. Ray)	16	19	18	19	0
Burlington, Iowa	4	15.5			
Beloit, Wis	3	25	17	31	− 6

[1] National Almanac for 1863.

Surely from the rough comparison of present-day records with those of 50 years earlier no widespread change of snowfall is indicated.

Probably the first set of maps representing the snowfall of the United States was published under the direction of Prof. Mark W. Harrington in 1894, then chief of the Weather Bureau (**9**). There are eight charts showing the snowfall for each month from October to May. Owing to the limited number of stations, particularly in the mountains, the distribution of snowfall could be shown in a general way only. The size of the individual charts, $7 \times 4\frac{1}{2}$ inches, gives a good indication as to the detail. Lines of equal snowfall are drawn for 0, 1, 3, 5, 10, 15, and 20 inches. The period used is from 5 to 20 years, most of the records being not over 7 years long (1884–1891).

The main features of the charts are the snowfalls in excess of 20 inches in the winter months in the Upper Lake region and northern New England. The January chart shows snowfall south to central Florida. In the very brief discussion accompanying these charts Prof. Harrington lays most emphasis on mountain snowfall.

In Prof. Frank Waldo's "Elementary Meteorology" (New York, 1896), a chart of the mean annual snowfall of the United States is given (1884–1891). The heaviest snowfall indicated is in the Lake Superior region. In the text, Prof. Waldo says that at low altitudes in the country as a whole snow seldom lies on the ground south of the 31st parallel nor south of the 33d on the coast of the South Atlantic States.

Prof. A. J. Henry, in the MONTHLY WEATHER REVIEW for March, 1898, published mean annual snowfall data for 159 regular Weather Bureau stations throughout the United States, and for 24 Canadian ones. The lengths of the periods vary between 3 and 11 years. These data are shown on a map by lines representing 0, 1, 5, 10, 20, 30, 50, and 100 inches of snowfall. Even with so few stations, the heavier snowfall on the east, than on the west shores of the Great Lakes, is indicated. The Appalachians have heavier snowfall than the plains east or west. The 0 line does not include all of Texas and but little of Florida.

In 1906 the Weather Bureau published a large work entitled "Climatology of the United States" as Bulletin Q of the Weather Bureau (**10**). For the United States east of the Mississippi the data presented are from 358 stations. Including the year 1903, most of the records are less than 15 years in length. In the general discussion the positions of the 5-, 50-, and 100-inch lines of equal annual snowfall are described. They correspond roughly to those on the chart presented below. In the voluminous tables which comprise most of the book (900 pages), the average depth of snowfall is given for each month, for each of the four seasons, and for the year. Also the greatest depth in 24 hours is given for each month. The data are arranged by States. At the beginning of the tables for each State is a general discussion of the topographic features, temperature, and precipitation. The details of snowfall distribution are mentioned, even to the extent of describing some severe snowstorms, particularly in the southern States. In connection with the maximum snowfall in 24 consecutive hours, the storm of March, 1888, is said to have set the record for the northeastern States, and the severe snowstorms of February, 1895, and February, 1899, for the southern States. In the discussion of the snowfall of Wisconsin the apparently greater snowfall in the northern and southern parts of the State, as compared with the middle, is ascribed to the relatively greater distance of the middle from cyclone tracks on the north and south in winter. The heavy snowfall of upper Michigan and western Ontario is attributed to the influence of the Lakes, which is felt on the south and east shores because the wind is prevailingly northwest in winter. Concerning South Carolina it is stated that, although the average snowfall is heaviest in the high western part of the State, the greatest 24-hour snowfalls occur in the center. This part is exposed more to the northeast winds which bring heavy snow.[2] Three snowstorms in Florida are mentioned, those of February, 1895 and 1899 (**11**), and December, 1901. Of these the first two gave 2 to 4 inches of snow in the northern part of the State.

Some snowfall means are contained in the "Summary of the Climatological Data for the United States by Section" (**12**). These were prepared from 1908 to 1912 by the section directors of the Weather Bureau. Monthly and annual snowfall means at 411 stations in the northern United States for periods of 4 to 39 years (usually including 1908) are published here. Snowfall is usually mentioned in the general climatological discussions accompanying each section. For instance, the influence of the Great Lakes is described. In the fall and early winter the high temperature of Lake Michigan frequently causes rain on the west shore of the lake while a snowstorm is in progress inland (**13**). Convenient topographic maps showing the climatological stations of the State are included in the summary for each section.

A chart representing the mean annual snowfall of the United States from 1895 to 1910, prepared by C. F. Brooks, was published in the Quarterly Journal of the Royal Meteorological Society, April, 1913. For the eastern United States data from about 700 stations were used.

SUMMARY.

Volney recognized the general relation between snowfall and the proximity of extensive moist surfaces. Forry, in addition, knew of the protective action of a snow cover on vegetation and sought to disprove the idea that snowfall is decreasing. Blodget, with some observations at his disposal, was able to give a good description of the snowfall in the eastern United States. The first maps showing the snowfall of the whole country were probably those prepared under the direction of Prof. Harrington. These were monthly maps and Prof. Waldo added an annual one to them. The increase in the number of observing stations and in the length of the snowfall records enabled Prof. A. J. Henry to produce a more detailed annual snowfall map in 1898. In 1906 he further described the snowfall of the United States, and six years later (1912) C. F. Brooks was able to map the snowfall in the mountainous parts of the country.

DISCUSSION.

Today, with still more data available, an extensive study of the snowfall of the United States is possible. As a first step, the snowfall of the eastern United States is here charted (charts C.F.B. 1–15) and discussed. The order of treatment of this subject will be: (1) extent and accuracy of data used; (2) discussion of the distribution of snowfall and the factors involved. The charts presented include: *a.* average monthly snowfall, September to May; *b.* average annual snowfall; *c.* average directions of snow-bearing winds, December, January,

[2] The snowstorm of Feb. 25–26, 1914, may be cited as an illustration of this. One foot of snow fell in the central region of South Carolina and Georgia, but less in the west and south. This snow was practically gone within a week. Prof. Henry states that this is usually true for the South Atlantic and Gulf States. Snow is considered a burden, for it is soon converted into slush.

February, and March; *d.* average annual number of days with 0.1 inch or more snowfall; *e.* special charts and diagrams illustrating the snowfall about the Great Lakes.

DATA.

All available published snowfall data for the stations east of the Mississippi River from July, 1895, to June, 1913, were tabulated by months (see fig. 2). This period begins with the general publication of the data from the cooperative stations of the Weather Bureau. Longer records were not used, since in order to bring out the true geographic relations of such a variable climatic factor as snowfall, homogeneity in time – i. e., a uniform fundamental period—is essential.[3]

The accuracy of these published data is doubtful in many instances. The observations of the depth of snowfall, usually made only once a day or once a snowstorm, contain serious errors due to drifting, wind and rain packing, melting, and evaporation(**14**). Further errors arise in the printing, tabulation, and reduction of the data. However, on the final maps, the effects of such errors seem to have been practically eliminated through the use of such extensive data.

The following table shows the extent of published snowfall records of different lengths for each State:

TABLE 2.—*Number of stations furnishing snowfall data for the United States east of the Mississippi River, 1895–1913.*

State.	Number stations having snowfall record for—						
	18 years complete.	18 years in part.	14–17 years.	10–13 years.	6–9 years.	1–5 years.	Total.
Alabama	16	10	8	14	18	29	95
Connecticut	5	2	6	5	2	8	28
Delaware	0	2	1	2	1	2	8
District of Columbia	1	0	0	1	0	0	2
Florida	5	....	....	36	....	42	83
Georgia	20	8	16	17	20	36	117
Indiana	16	11	14	13	15	37	106
Illinois	21	16	25	23	19	71	175
Kentucky	9	9	12	10	10	31	81
Maine	4	3	4	6	8	22	47
Maryland	13	4	8	9	16	29	79
Massachusetts	8	5	8	14	11	47	93
Michigan	15	19	38	32	33	50	187
Minnesota [1]	4	3	1	2	6	1	17
Mississippi	27	2	9	11	15	46	110
New Hampshire	5	5	1	4	3	20	38
New Jersey	8	10	17	12	19	29	95
New York	15	10	40	30	42	112	249
North Carolina	12	12	10	18	22	55	129
Ohio	30	26	27	13	36	81	213
Pennsylvania	14	7	21	26	39	48	155
Rhode Island	4	1	0	1	1	1	8
South Carolina	24	1	14	8	4	23	74
Tennessee	18	5	23	11	16	39	112
Vermont	3	3	3	3	4	15	31
Virginia	11	4	15	7	23	55	115
West Virginia	4	11	16	20	11	45	107
Wisconsin	13	17	14	15	15	69	143
Total	325	206	351	363	409	1,043	2,697

[1] East of the Mississippi only.

The data were reduced with the aid of an adding machine. The monthly and annual averages obtained were first plotted on large scratch maps of the individual States and the lines of equal snowfall were then drawn. On the monthly charts lines for 0, 1, 2, 5, 10, 15, 20, 30, and 40 inches were used, and on the annual, those of 0, 1, 2, 5, 10, 20, 30, 50, 70, 100, and 130 inches. In drawing these lines I used only the means based on records for the entire 18 years, except where stations with such records were too far apart. For most States, the records 14 to 17 years long sufficed to fill in the gaps. But in the sparsely populated regions of Minnesota, Wisconsin, and Michigan and in the Appalachian region, still shorter records were used. However, none less than six years long was considered. So in these regions, at least, the charts are far from satisfactory as accurate representations of the true snowfall. In the Southern States, and everywhere for the fall and spring months, all records showing any snowfall at all were used in determining the position of the zero line.

These charts represent the average monthly and annual snowfall from 1895 to 1913 only. With a longer period, many of the "islands" and some peculiar loops in the lines would probably disappear. This would apply particularly to the snowfall of the southern States, since there the average amounts are calculated from but few snowstorms.

The data for the charts of snow-bearing winds for the months December, January, February, and March were procured from the U. S. Daily Weather Maps (Washington) for these months for the 18 years from 1895 to 1913. The principle on which the wind roses were made is roughly the same as that employed on the monthly pilot charts of the U. S. Hydrographic Office. For instance, take the wind rose for Boston in December (chart C.F.B. 4). In the 18 years there were 31 occurrences of snow at 8 a. m. These were distributed as follows:

Wind direction.	N.	NE.	E.	SE.	S.	SW.	W.	NW.	Calm.
Occurrences	16	3	2	1	1	1	0	7	0
Per cent of total	52	10	6	3	3	3	0	23	0

On the original map the length of the north arrow was drawn 0.52 of an inch long; that of the northeast arrow, 0.10 inch long, and so on. To take an extreme case, Vicksburg had but two occurrences of snow, one with a north wind and the other with a west wind. Thus there were but two arrows, each 0.50 inch long. The percentage of occurrences with no wind is indicated by a figure in the center, absence of any figure meaning 0.

THE AVERAGE DISTRIBUTION OF SNOWFALL.

The average distribution of snowfall in the eastern United States is much the same as that produced by a single cyclone. Northern regions well exposed to winds blowing from moist surfaces receive the heaviest snowfall. Thus the country about the Great Lakes and the North Atlantic States gets heavy winter snows. Farther south, although there is plenty of moisture, the temperatures accompanying precipitation in winter are not so favorable to snowstorms.

The Great Lakes region, the Atlantic Coast States, the Appalachians, the Gulf States, and the central valleys have distinct snowfall characteristics. Each region will now be considered separately.

The snowfall about the Great Lakes.

Perhaps the most striking feature of the early snowfall charts of the United States was the heavy snowfall indicated in the Lake region. Now, with a large number of stations and a comparatively long series of observations, the details can be studied.

For this purpose, the accompanying supplementary charts and diagrams (figs. 3–10) have been drawn. Figure 3 indicates the mean annual snowfall about the Great Lakes from 1895 to 1910. The data from about 100 stations were used, many records being incomplete.

[3] *See* MONTHLY WEATHER REVIEW, Washington, April 1902, 30: 205-243.

In the region north and east of Lake Superior there are but three stations; so there, at least, the chart is only approximate. A longer series of years would have been used had there been more stations prior to 1895 or had the Canadian snowfall data after 1909 been published. Nevertheless, the general snowfall about the Great Lakes is indicated with some degree of accuracy. In general, it is to be seen that the snowfall is heavier in the north than in the south, and much heavier on the east shores

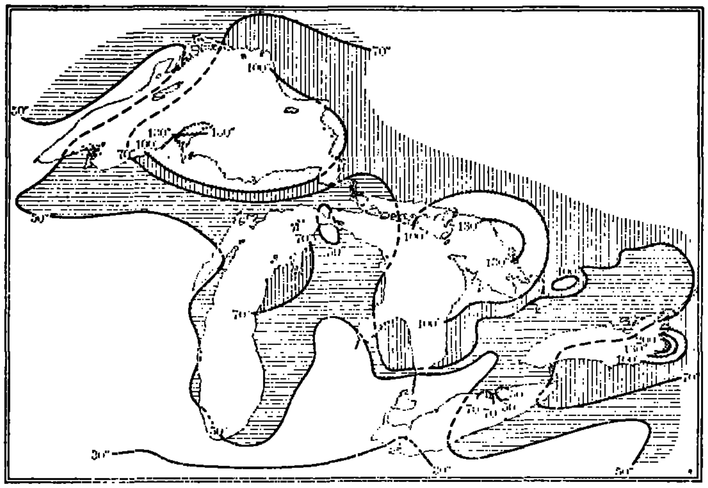


FIG. 3.—Average annual snowfall about the Great Lakes, 1895-1910 (100 stations). (Mercator projection.)

than on the west. For instance, Port Arthur has 31 inches and White River 93, Duluth 49, Calumet 136, Chicago 36, South Bend 63, Sandusky 29, Buffalo 78, Toronto 51, Adams 200.

Figure 4, representing the minimum annual snowfall for any year 1895–1910, looks much like the mean annual chart with some exceptions. For instance, the minima at Calumet and Adams are about the same; also Port Arthur and White River have equal minima.

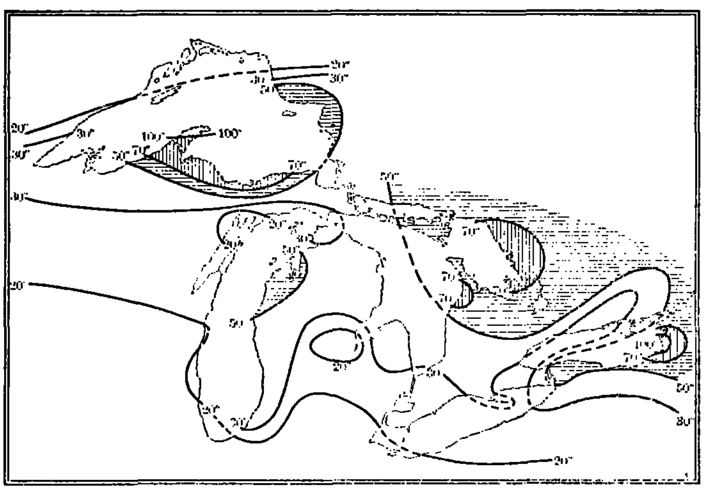


FIG. 4.—Minimum annual snowfall about the Great Lakes, 1895-1910. (Mercator.)

Figure 5, the maximum annual snowfall for the same period, also shows close resemblance to the annual snowfall distribution. The absolute maximum of 334 inches occurring at Adams is far in excess of that measured elsewhere in this region.

Figure 6 shows the difference between these maxima and minima. The most striking range is that of 134 inches at White River. This is nearly twice that at Calumet, where the mean annual snowfall is much greater. The large range of 229 inches at Adams is of little consequence, for the minimum is above 100.

The four diagrams represent monthly snowfall in inches and in per cents of the mean annual for different regions on the Lakes. Figures 7 and 9 are for the northern Lake region, west and east shores, respectively, and figures 8 and 10 for the southern Lake region, west and east shores. In figure 7, for the western shores of the northern Lake region, the five stations—Port Arthur, Ontario; Du-

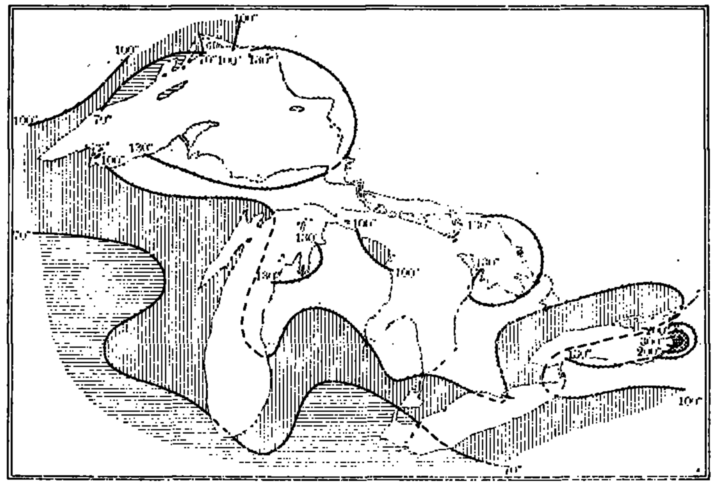


FIG. 5.—Maximum annual snowfall about the Great Lakes, 1895-1910. (Mercator.)

luth, Minn.; Escanaba, Alpena, and Cheboygan, Mich.—have been used. The mean annual snowfall (1895–1913) for these five was 49 inches. There is one column for the snowfall of each month from September to May. The scale on the left is in inches of snowfall for the middle part of each column and the per cent of the annual mean for the edges. The snowfall is fairly evenly distributed through the winter months, but with a slight minimum in January and a maximum in February.

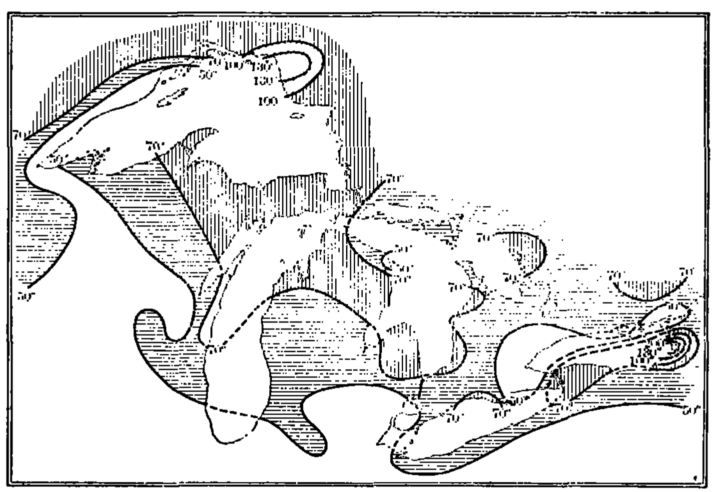


FIG. 6.—Extreme range of annual snowfall about the Great Lakes, 1895-1910 (fig. 5 minus fig. 4). (Mercator.)

Figure 8, for the west shores of the southern Lake region, is based on observations at Milwaukee, Wis.; Chicago, Ill.; Detroit and Port Huron, Mich.; Toledo, Ohio; and Toronto, Ontario. There is a slow rise to a late winter maximum in February followed by a rapid decline. The annual mean for the stations is 45 inches.

Figure 9, for the east shores of the northern Lake region, was made from observations at Calumet, Sault Ste. Marie, and Charlevoix, Mich.; Saugeen (Southampton) and Parry Sound, Ontario. The annual mean is 103 inches—a sharp contrast to that of the west shores. The snowfall at these stations comes rapidly to a maximum in December and then slowly decreases.

Figure 10, representing the snowfall of the east shores of the southern Lake region, is based on observations

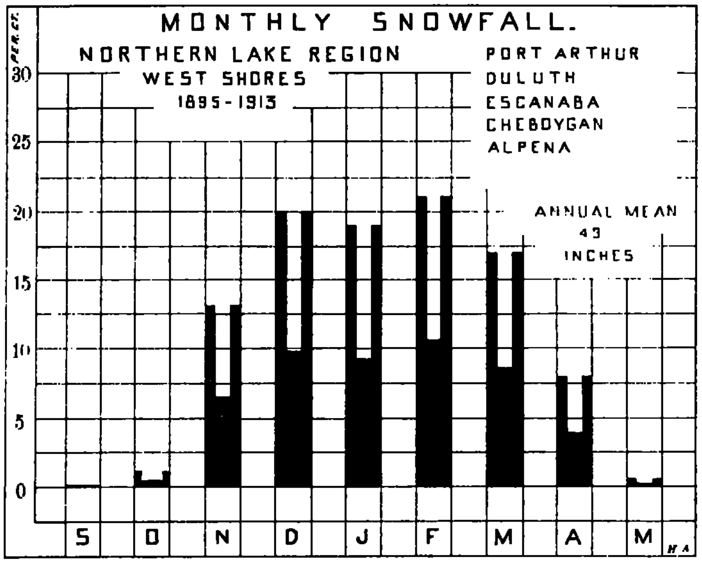


FIG. 7.—Percentage monthly snowfall for the western shores of the northern Great Lakes. (Mercator.)

from Cleveland, Ohio; Erie, Pa.; Buffalo, Oswego, and Adams, N. Y. The annual mean is 81 inches and the maximum comes in January.

The snowfall in the Lake region is derived from the abundant moisture precipitated at low temperatures by the frequent winter cyclones. The prevailing northwest winds and the relative nearness to the Atlantic and the

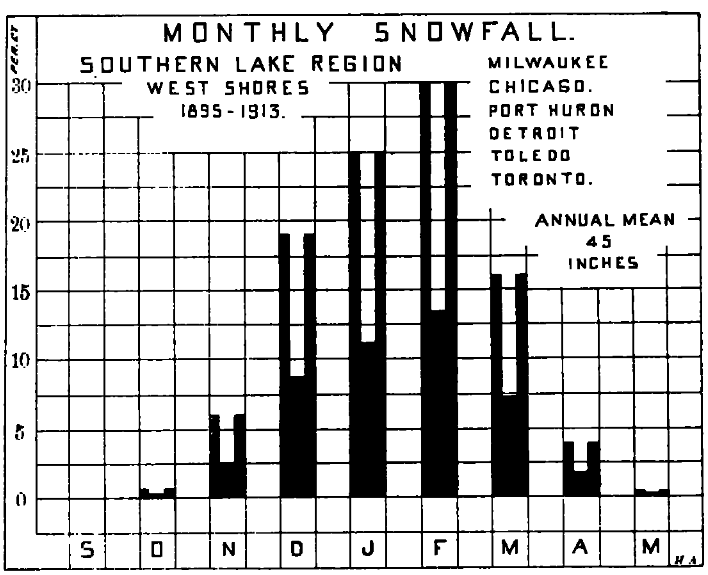


FIG. 8.—Percentage monthly snowfall for the western shores of the southern Great Lakes. (Mercator.)

Gulf of Mexico combine to make the eastern and southern Lake region more moist than the western and northern. In consequence there is generally diminishing winter precipitation northwestward, with local maxima on the leeward shores of the Lakes. The same would be true of snowfall if all the precipitation were in the form of snow.

In the south, however, the temperature during precipitation in winter is frequently too high for snow. So, although the maximum precipitation occurs in the southeast, the maximum snowfall is in the east and northeast. However, in the colder winters the snowfall in the south becomes heavier than in the north because more of the

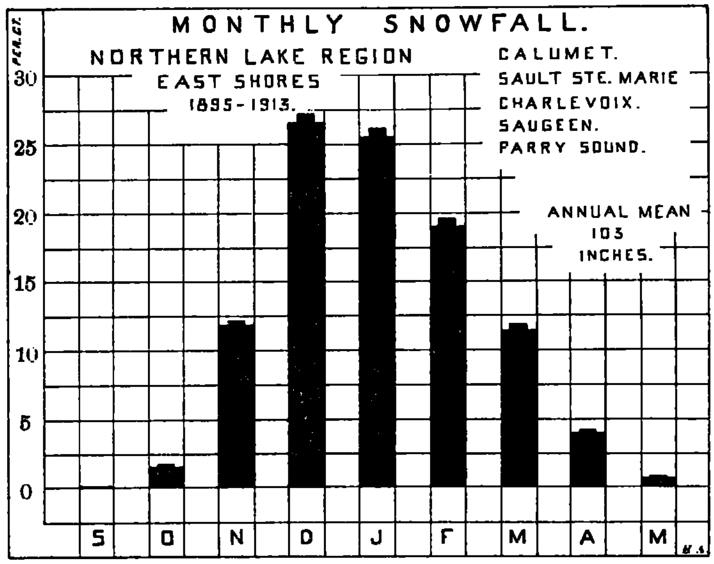


FIG. 9.—Percentage monthly snowfall for the eastern shores of the northern Great Lakes. (Mercator.)

normally greater precipitation occurs as snow. The deficiency of northern snowfall relative to southern in such cold periods is further accentuated by a decrease in the amount of snowfall in the north. This is due to the reduced moisture capacity of the colder air and to lack of normal cyclonic activity. The distribution of snowfall by months, as indicated in figures 7 to 10, shows this difference in the effect of lower temperatures on snowfall.

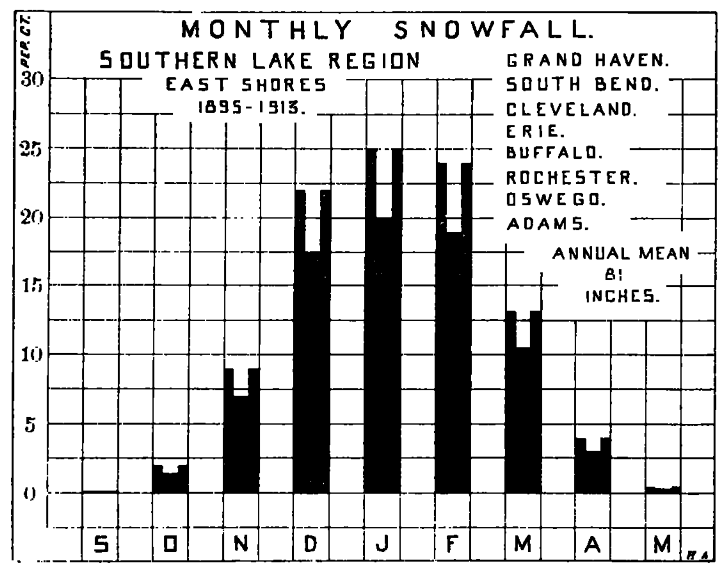


FIG. 10.—Percentage monthly snowfall for the eastern shores of the southern Great Lakes. (Mercator.)

Thus figures 7 and 9 for the north indicate the snowfall maxima in months which are not the coldest, while figures 8 and 10 for the south show the heaviest snowfall in the coldest winter months.

As was indicated in the discussion of the distribution of snowfall in cyclones (11), moist cyclone winds in winter cause increased precipitation when blowing from a comparatively warm water surface over cold land. The cooling which produces this precipitation is caused partly by mixture and radiation but chiefly by forced ascent of the wind, due to increased friction and to topography. The result is heavy snowfall on leeward shores; since the prevailing winds over the Lakes are west or northwest, the leeward shores are the east ones. The usual low temperature of the northwest winds makes their precipitation generally snow in winter.

The Lakes being warmest and mostly open early in winter, the leeward maximum tends to come then, but it is delayed by temperatures too high for snow. In the northern Lake region, the maximum occurs in December, but in the southern not until January, although December has heavy snowfall (see figs. 9 and 10).

The large variability of snowfall on the windward shores may be explained by the variable conditions of cyclonic action on which these shores depend almost entirely for their snowfall. The snowfall of the eastern shores is made up of the fairly regular west-wind snowfall in addition to the irregular cyclonic snowfall and so shows less proportionate variation.

Figures 3 to 6 and charts 1 to 15 show the detailed effects of the Great Lakes and winds on the distribution of snowfall in this region. Early in winter the snowfall of the immediate shores is generally less than that a short distance inland. For instance, notice the snowfall of the Keweenaw Peninsula. Early in winter the snowfall on the Lake shore is but little more than half as great as that 1,000 feet higher; late in winter, the snowfall of the shore equals that of the higher land. A case in which distance from the warm water made heavy snowfall possible is that of the night of November 2, 1911. An "unprecedented fall of 18 inches (of snow) occurred at South Bend, Ind., although there was but little or none at any of the surrounding stations on that date" (15). On the other hand, snowstorms are sometimes confined to the very shores of the Lakes. The October snowfall indicated on the southeastern shores of Lakes Michigan and Erie (chart 2) is nearly all the average of two snowstorms in 1906 and 1910. Each gave more than a foot of snow near the Lakes, the heaviest falls occurring in southwestern Michigan. The snowfall of one of these storms was only a trace but 25 miles inland. Both occurred with onshore winds following the passing of cyclones. Such is the local character of early Lake snowstorms.

Later, as the Lakes become cooler, the snowfall on the shores approaches the amounts received inland. Also the snow-bearing winds from the water increase in number relative to those from the land (see charts 4, 6, 8, and 10). Some of the late-winter increase of the shore snowfall relative to that a short distance inland might be explained by snow drifting off the Lakes. Ice floes moving about with the wind collect at the leeward sides of the Lakes and there present a fairly flat surface from which the winds blow snow onto the land. There in the weaker wind the snow is deposited, augmenting snowfall.

Strips of snowfall heavier than inland are indicated on the west shores of Lakes Huron and Michigan in December, January, February, and the year (charts 5, 7, 9, 15). These are evidently from the easterly winds which come with heavy snow in the northeast quadrant of strong winter cyclones. The heavier snowfall in southern Wisconsin than in the center, spoken of by Prof. A. J. Henry (see p. 4), is not indicated on these charts. In February only is there a suggestion of this and on the annual chart (chart 15) there is no evidence of such a peculiarity.

In spring the warmth of the land relative to the water more or less counteracts the cooling tendency of on-shore winds and so tends to prevent precipitation. Thus the mid-winter areas of heavy snow on the east shore of Lake Michigan become in March and April strips of snowfall less than that received away from the direct influence of the lake (see charts 7, 9, 11, and 12). This effect is shown also by the diminishing percentage of snowfall with winds from the Lakes from February to March (see charts 8 and 10). In May, June, August, and September snowfall occurs in small amounts about the Lakes, particularly near Lake Superior and on the high land not far from the other lakes.

Most of the wind roses about the Great Lakes (charts 4, 6, 8, and 10) do not show any striking prevalence of snow with winds from the Lakes. Nevertheless, the snowfall is much heavier on the east shores than on the west. Although the surface wind may be from any direction during snowfall, still overhead atmospheric movements which are prevailingly from the west bring the moisture eastward from the Lakes. Furthermore, since the wind roses were made on the basis of the mere occurrence of snow at 8 a. m. without reference to the intensity of snowfall or to the force of the wind, they do not show which winds bring the major portion of the snowfall.

Conclusions.—In winter all parts of the Lake region are subject to snowfall from general cyclonic storms. Such storms may account for perhaps 30 inches of the annual means. The remainder is probably due to the effect of local topography on cold, moist winds. Thus the cold northwest winds of winter after crossing a lake deposit considerable snowfall on the eastern shores. The western shores get a little local snowfall from the infrequent northeast winds. The shore snowfall topographically produced, tends to reach a maximum early in winter when the winds from the relatively warm Lakes experience the greatest cooling on reaching land.

The snowfall of the Appalachian Mountains.

In the Appalachian region, the greater the altitude, the heavier is the snowfall, as a general rule. In the north, and even south to West Virginia, the higher country receives more than 100 inches a year. The high mountains of North Carolina apparently get less than 50 inches annually (see chart 15) (16). The average monthly snowfall reaches a maximum of about one-quarter of the annual, this maximum occurring usually in January, but in February in New England.

The monthly charts show the progressive advance and retreat of the snowfall lines from September to May. Snowfall has been recorded in June south to Virginia and West Virginia, and in August in the Adirondacks. Apparently no record of July snowfall in this region is contained in the published tables of the Weather Bureau from 1895 to 1913. However, snowfall in this month has occurred on Mount Washington at least (17).

While the temperature control of latitude and altitude on snowfall are important, the exposure to snow-bringing winds and the proximity of water surfaces to windward can not be overlooked. As examples, take three areas of very heavy snowfall in the Appalachians—the western Adirondacks, the southern Green Mountains, and the mountains of West Virginia.

The first is represented by the station Number Four, N. Y., situated at an altitude of 1,571 feet above sea level and freely exposed to the west. The mean annual snowfall there is 166 inches, as shown by eight years' records. The month of heaviest snowfall is December, with 37 inches; January, February, and March all have more than 30. As was indicated in the discussion of the snowfall about the Great Lakes, leeward shores have heavy snowfall, and excessive snowfall where topographic features strongly force the ascent of moist winds. Number Four, close to Lake Ontario, with the other Great Lakes not far to windward, is excellently situated to receive heavy snowfall, which, with the topographic effect added, becomes profuse. Lowville, about 15 miles west of Number Four, nearer Lake Ontario, at an altitude of 900 feet above sea level, receives on the average (15 years) but 92 inches a year. Blue Mountain Lake, 40 miles east

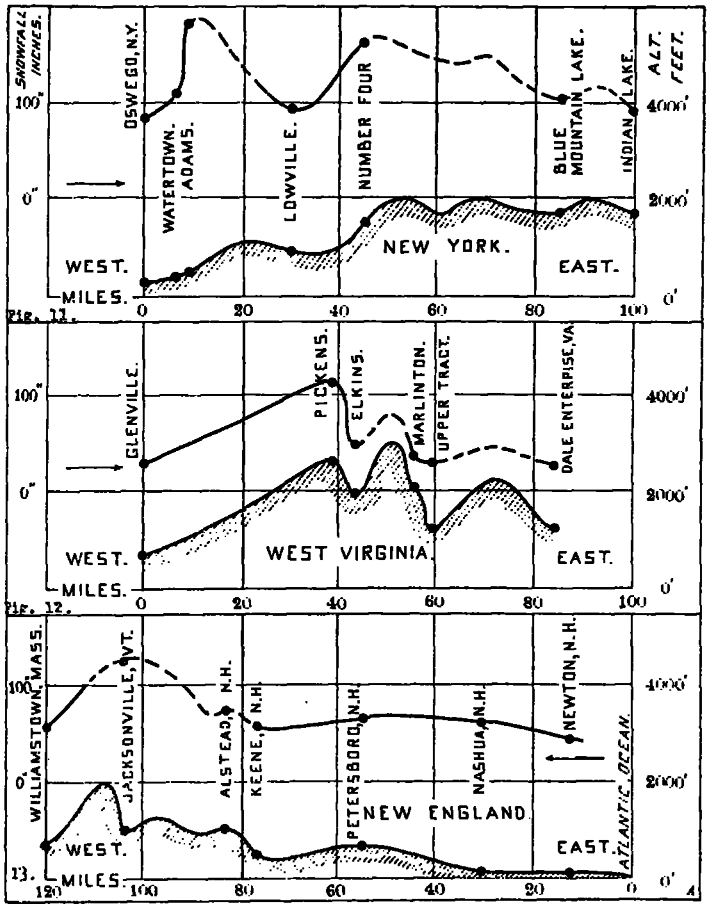


FIG. 11.—Distribution of snowfall across northern New York from Lake Ontario eastward.

FIG. 12.—Distribution of snowfall across West Virginia.

FIG. 13.—Distribution of snowfall across New England from the New Hampshire coast to Williamstown, Mass.

In all these figures the arrows indicate the snow-bearing winds; the shaded curves indicate the topography.

of Number Four, 1,750 feet above sea level, has an average annual snowfall of 105 inches (10 years). Indian Lake, 10 miles farther east, altitude 1,705 feet, still more in the snow shadow of the western Adirondacks, has an average annual snowfall of 92 inches. Thus the excess of snowfall of Number Four over the lower station on the west and the higher ones on the east may be ascribed to its altitude on the one hand and to its exposure on the other. The wavelike distribution of snowfall in northern New York, from Lake Ontario eastward, is quite marked. Figure 11 shows this graphically.

The second region, West Virginia, has its maximum snowfall at Pickens on the west slope of the Appalachians. Pickens is at an altitude of 2,785 feet above sea level and has an average annual snowfall of 111 inches (11 years). The wind roses for Elkins (charts 4, 6, 8, and 10) have the west wind prominent in every case, for when the moist winds of the Ohio Valley reach the Appalachians they are forced to ascend rapidly more than 2,000 feet, with the result that in winter snow usually falls with any strong west wind. The first ridge very apparently casts its snow shadow on the country behind, so that on the lee side the snowfall is the same at 1,000 feet elevation as at 700 feet on the windward side. (See fig. 12.)

The Green Mountains of Vermont become progressively snowier southward. This is not due to the increase in altitude, but to more open exposure to the moist easterly winds from the Atlantic. The snowfall at Jacksonville, Vt., 1,000 feet above sea level, on the east slope of the southern part of the mountains, represents the culmination of the effects of this exposure and of topography in this region. The average annual snowfall there is 124 inches (15 years). On the other side of the ridge, Williamstown, Vt., at 711 feet altitude, has but 50 inches of snowfall annually (16 years). Figure 13 is a general snowfall and altitude profile from the Atlantic Ocean across southern New Hampshire and Vermont to the west side of New England. The heavy snowfall at Jacksonville is probably caused by the east winds from the Atlantic and north winds from up the Connecticut Valley, passing over the mountains there. The east winds are moist and the north winds cold, and their passage over the mountains in southern Vermont is probably favored by the eastward turn of the Connecticut Valley at that point, which hinders a further southward flow of air. Places on the west side of the Green Mountains are in the snow shadows of both the Green Mountains and the Adirondacks, and so have relatively little snowfall. In northern New England west-wind snowfall is again encountered in large amounts where the winds from the St. Lawrence Valley cross the mountains. From these examples it is apparent that that free exposure to moist winds leads to heavy snowfall at a mountain station in winter.

The snowfall of the Atlantic coast.

The northeast snowstorm of the Atlantic coast is one of its emphatic winter characteristics. Whittier's "Snow-bound" is the classic description of such a storm in New England. The snowfall of the north Atlantic coast is very heavy in some winters, but almost lacking in others. The average annual amounts (see chart 15) approach 100 inches in Maine but decrease rapidly southward. A short distance inland away from the tempering influence of the Atlantic and in a region cooler because of greater altitude, the snowfall is heavier than on the coast as was the case about the Great Lakes. At points still farther back the snowfall is less because they are beyond the pale of the coast snowstorms. Thus the snowfall in south central Maine is less than that on the coast and less than that of the higher land to the north. This is shown on the charts for February, March, April, and the year (charts 9, 11, 12, 15). The same effect is also shown on the coastal plain of Virginia and North Carolina in October (chart 2). October snowfalls have occurred in this coastal area not once but several times in the 18 years.

On the whole, the month of maximum snowfall is February, although January snowfall equals that of February on the middle Atlantic coast. For the south Atlantic coast nearly all of the snowfall represented on the February chart came in February, 1899 (**11**, figs. 1–6). Even for the middle Atlantic coast, the omission of that one month in the whole period would mean a difference of 2 to 3 inches in the February and annual means. The snowfall lines on the April chart (chart 12) follow topography more closely than on any other. This may not be due so much to differences in the actual amount of snow fallen as in that which accumulated on the ground. For ground temperatures in spring and fall are such that, on a hill, snow will accumulate on the ground while in an adjacent valley but a few hundred feet lower, the ground may be just warm enough to melt the snow as it falls. Thus, on Blue Hill, Mass., the light snowstorms of fall and spring frequently cover the ground 2 inches deep, while, at the same time in the Boston basin a few miles north and but 500 feet lower, the snow melts as it strikes the ground. The accumulated effect of the difference due to altitude and city heat is such that Blue Hill has an annual snowfall mean of 58 inches as compared with 41 for Boston (1895–1913).

As is clearly shown on the December chart of snow-bearing winds (chart 4), snow on the immediate coast does not usually occur with the surface wind blowing off the comparatively warm ocean. Later, when the water has become relatively cold, snow occurs most frequently with easterly, particularly northeasterly, winds. Friction and topography become effective snow producers with the late-winter snow-bearing winds which blow on shore, as is the case with the snowfall about the Great Lakes. The delay of the maximum snowfall until February is due to the retarding effect of the ocean's heat. Coast cyclones are more generally accompanied by snow in this month than in any other.

Thus most of the snowfall on the Atlantic coast is the result of moist air from the Atlantic Ocean cyclonically and topographically cooled.

The snowfall of the Gulf States.

The snowfall of the Gulf States may be described as occasional. On this account the charts showing average snowfall per month or year give an erroneous impression. For instance, at Montgomery, Ala., a total of 14 inches of snow fell during the 18 years from 1895–1913. This came in only four months:

	Inches.
1899—January	3.[illegible]
February	3.0
December	3.5
1901—February	4.0

Amounts too small to measure occurred as follows:

	Times.
November	2
December	6
January	6
February	7
March	2
April	1

Thus the annual mean of 0.8 inch tells one almost nothing of the character of the snowfall at Montgomery. This is typical of the South.

Similarly, the data on which the wind roses were constructed (charts 4, 6, 8, and 10) are deficient. However, they do show that when the snow did occur it was, almost without exception, with a northerly wind. The snowfall which occurs with northwest winds is usually of the snow-flurry type, just as it is over most of the eastern United States. On the other hand, the snow which comes with a north or northeast wind is frequently heavy enough to accumulate on the ground (see charts 11 and 12).

Since unusually cold weather must prevail in the Gulf States to allow snowfall there, the snow generally occurs under high pressure conditions. A cold high pressure area over the southern Ohio Valley and the southern Appalachians necessarily sets up a convectional circulation with the warm air over the Gulf of Mexico. The result is precipitation that often starts as rain, but frequently becomes snow as the circulation increases in intensity. The storm of February 10–14, 1899, is an excellent illustration of the development of such a storm.

The effect of altitude on the snowfall of southern Alabama and Mississippi is shown by the snow "island" on the southern cuesta (see chart 12) and by the areas of less snowfall north of it (see chart 15).

In brief, snowfall in the Gulf States is uncommon. Occasional snow flurries occur when strong winter cyclones pass on the north; but most of the snow comes with the northerly winds of anticyclones.

The snowfall of the upper Mississippi and Ohio Valleys.

The snowfall of this great flat region is moderate, diminishing southward and westward. Even the slight topographical features are sufficient to make the snowfall lines contour lines, to some extent. Much of the sinuosity of these lines can be explained by the snowfall of a few heavy snowstorms. One storm late in April, 1901, gave from 1 to over 3 feet of snow in the upper Ohio Valley. The effect of this storm is plainly visible in the large southward bends of the 2-inch and the 1-inch lines in Ohio on the April chart (chart 12). The snowfall chart for April, 1901, in the MONTHLY WEATHER REVIEW for that month shows the general distribution of snow in this storm. Many other irregularities in the snowfall lines due to single storms may be picked out on the maps.

In the Ohio Valley the maximum snowfall comes in February, the coldest month. On the other hand, in the upper Mississippi Valley the maxima are in December and March. The low temperatures of January and February in the Northwest generally prevent heavy snowfall in these months, both by limiting the amount of moisture in the air and by favoring anticyclonic air circulation.

The charts of the wind roses indicate northwest-wind snowfall as the most frequently occurring type. However, the heavy snow comes with north to east winds. These winds carry moisture from the Great Lakes, Atlantic Ocean, and the Gulf of Mexico (through cyclonic action) while those from the northwest blow from the dry continental interior. When the appropriate morning and evening weather maps are compared with the charts of snowfall in my earlier paper (**11**), the contrast between the snowfall of these winds is readily discernible. In general, the snowfall in the central valleys is not often heavy. This is because of dryness in the northwest and warmth in the east.

CONCLUSION.

The average distribution of the snowfall of the eastern United States is generally controlled by winter temperatures and the amount of moisture in the air. On account of their low temperatures and dampness, the Lake region, Appalachians, and north Atlantic coast get the heaviest snowfall. On the other hand, the Ohio Valley, the south Atlantic and Gulf States are usually too warm for much snow. In the northwest the snowfall is moderate because of the winter dryness. Within these larger snowfall provinces, the snowfall is locally modified by the topography and the exposure to moist winds. Thus, the Appalachians get heavier snows on their western than on their eastern slopes (except in Vermont), and the eastern shores of the Great Lakes get more snow than the western.

Snow generally falls in connection with winter cyclones, for the cyclonic action and the effect of topography on the winds cause precipitation. As the northeast wind is both cold and damp over practically the whole eastern United States, it is the wind of the great snowstorms. The northwest wind, although cold, is generally dry and so brings, at most, only snow flurries except locally on a windward mountain slope or in the lee of the Great Lakes. In brief, the main factors which control snowfall are temperature, moisture in the air, exposure to moist winds, local topography, and the passage of winter cyclones.

REFERENCES AND NOTES.

(1) *See also* American Almanac for 1837, p. 169–185: "Notices of remarkably cold winters."

(2) Some other journals with less extensive records are:

Cleaveland, Parker. Results of meteorological observations made at Brunswick, Me., 1807 to 1857.

Caswell, Alexis. Results of meteorological observations made at Providence, R. I., from December, 1831, to May, 1860.

Hill, Leonard. Meteorological and chronological register, 1806 to 1869 at East Bridgewater, Mass. Plymouth, Mass. 1869.

(3) *See* J. P. Espy's reports in the Journal of the Franklin Institute, Philadelphia, 1839 to 1841.

(4) *See* Report of the **Smithsonian Institution** for 1855: Directions for meteorological observations, adopted by the Smithsonian Institution for the First-Class observers.

(5) **U. S. Weather Bureau.** Annual report of the Chief, 1891–92. Washington, 1893, p. 447.

(6) A history of meteorological observations in the United States is attempted by Marcus Benjamin in the work "The Smithsonian Institution, 1846–1896" (Washington, 1897) on pp. 647–678.

More complete details are given by various authors before the International Meteorological Congress, held at Chicago, Ill., August 21-24, 1893. (*See* U. S. Weather Bureau Bulletin 11. pp. 207–220, 232–302.)

(7) **Volney, C. F.** A view of the soil and climate of the United States of America. Translated from the French by C. B. Brown. Philadelphia, 1804.

(8) **Blodget, Lorin.** Climatology of the United States, and of the Temperate Latitudes of the North American continent. Embracing a full comparison of these with the climatology . . . of Europe and Asia. . . . Including a summary of the statistics of meteorological observations in the United States condensed from recent scientific and official publications. Philadelphia. 1857. xvi, [17]–536 p. 4°.

An appreciation of this monumental work will be found in the MONTHLY WEATHER REVIEW, January, 1914, **42**: 23–27.

(9) **U. S. Weather Bureau.** Rainfall and snow of the United States as compiled to the end of 1891, with annual, seasonal, monthly, and other charts. Text and Atlas. Washington. 1894. 80 p. 4°. Atlas: 23 charts, 18 x 24 inches.

This publication is reviewed in Amer. meteorol. jour., Boston, Mass., June, 1895, **12**: 71–2.

(10) **Henry, A. J.** *& others.* Climatology of the United States. Washington. 1906. 1012 p. 33 pl. 4°. (U. S. Weather Bureau bulletin "Q." W.B. no. 361.)

(11) *See* MONTHLY WEATHER REVIEW, Washington, June, 1914, **42**: 318–330.

(12) **U. S. Weather Bureau.** Summary of the climatological data for the United States by Sections 106 [sections]. Printed at various section centers. 1908–1912. var. pag. 4°. (Bulletin "W." W.B. no. 476.)

(13) Such an effect is clearly shown on the U. S. Weather Bureau "Snow and Ice Bulletin" for December 30, 1913.

(14) For a thorough study of the physical changes which take place in a snow-cover, *See* —

Jansson & Westman, J. Quelques recherches sur la couverture de neige. Bull., Geol. instit. of Upsala, 1901, No. 10, **5**, pt. 2, pp. 234–260.

(15) *See* MONTHLY WEATHER REVIEW, November, 1911, **39**: 1671; also Chart VIII in the REVIEW for November, 1911.

(16) The United States Forest Service official living at an altitude of 5,060 ft. on Mount Pisgah, N. C., 18 miles southwest of Asheville, N. C., recently told the writer that the snow accumulated on the ground, sometimes to a depth of 3 feet, and that in one night a snowfall of 27 inches occurred. The similarity between these extremes and those met in eastern Massachusetts, suggests that the average snowfall in the southern Appalachians may be about 50 inches annually.

(17) **Greely, Adolphus W.** American Weather. p. 162.

I.

THE RAINFALL OF THE NORTHEASTERN UNITED STATES.

By B. C. WALLIS, B. Sc. (ECONOMICS). F. R. G. S., F. S. S.

[Dated: North Finchley, England, Sept. 21, 1914.]

THE METHOD OF INVESTIGATION.

Probably the two most important considerations regarding the rainfall of any area are its total quantity and its distribution through the year. Attention is called in this paper to the second consideration, and an attempt has been made to measure the distribution by means of the statistical method of differences. The amount of rainfall which would be precipitated at a given place, upon the assumption that such rainfall were evenly distributed through the year, has been taken as a *norm*. This *norm* is obtained by dividing the total annual fall by 365, and by multiplying the quotient by 28, 30, and 31, respectively, to obtain the numbers which represent the norms for the month of February, and for the 30- and 31-day months. The value of the norm has been taken for each month for all places as 100, so that in the accompanying maps (figs. 2–5, 12–23),

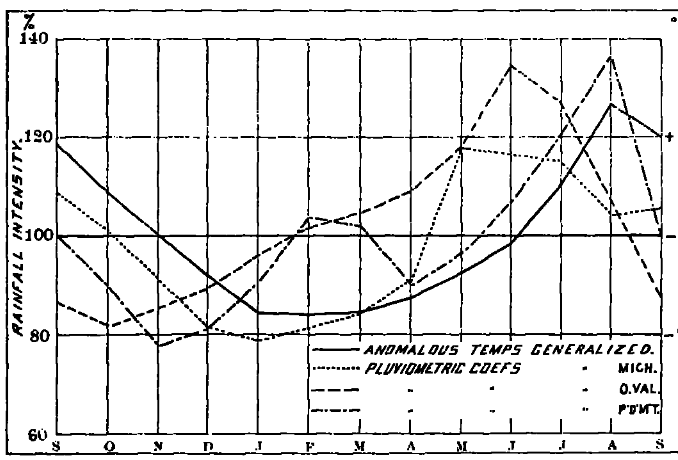


FIG. 1.—Annual march of pluviometric coefficients for Michigan, Ohio Valley, and the Piedmont compared with the annual march of the temperature anomalies for the northeastern United States.

the line which is marked 100 indicates that the rainfall at all places along that line is the norm for the month. Differences from the norm are expressed as percentages. Suppose the norm for a given place for January is $2\frac{1}{2}$ inches, and the actual average rainfall at that place for January is 3 inches; then since, when $2\frac{1}{2}=100$, $3=120$, the difference for that place for January is 120, which implies that during January at that place the precipitation is 20 per cent above the norm; i. e., January is a relatively wet month.

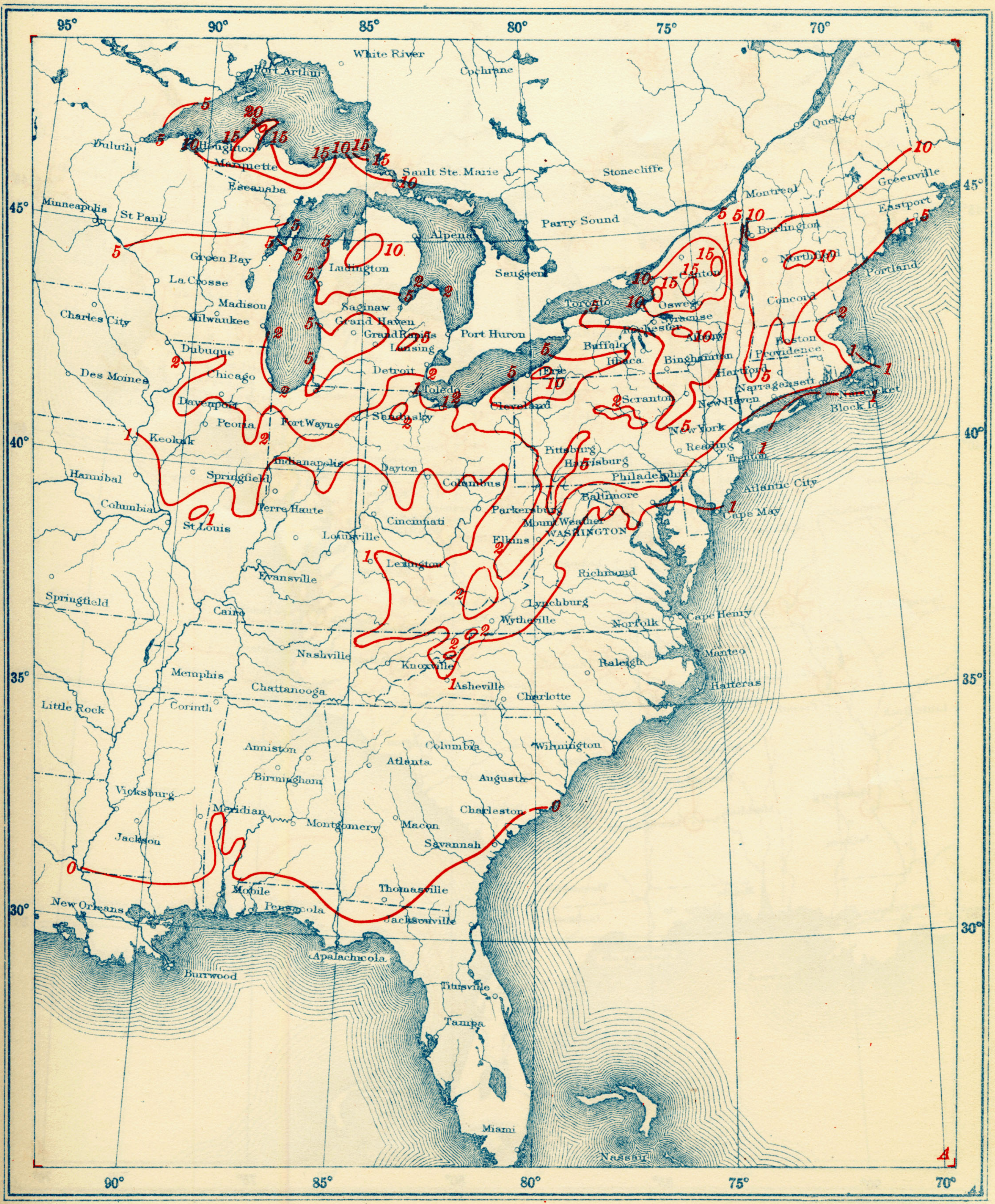
The name "pluviometric coefficient" has been given to this quantitative expression by Dr. A. Angot, who is responsible for this application of the method of differences to rainfall studies. When pluviometric coefficients are indicated upon maps, upon the same principles as isohyets, the lines of equal departure from the rainfall norm have been called by the present writer "equipluves,"[1] using a Latin term for the sake of greater

[1] Mr. Ernest Gold (4) has pointed out that the "pluviometric coefficient" is "the ratio of the mean daily rainfall of a particular month to the mean daily rainfall of the whole year."

The term "isomer" has been suggested by Mr. C. Salter (4) in place of the term "equipluve" coined by Mr. Wallis. If the former term is used one should be careful to preface it with the word "rainfall" or "precipitation," since in itself "isomer" does not suggest a quality of rainfall. This disadvantage is absent from the term "equipluve."—[C. A., jr.]

C. F. B. 1.—Average September snowfall (inches) over the eastern United States.

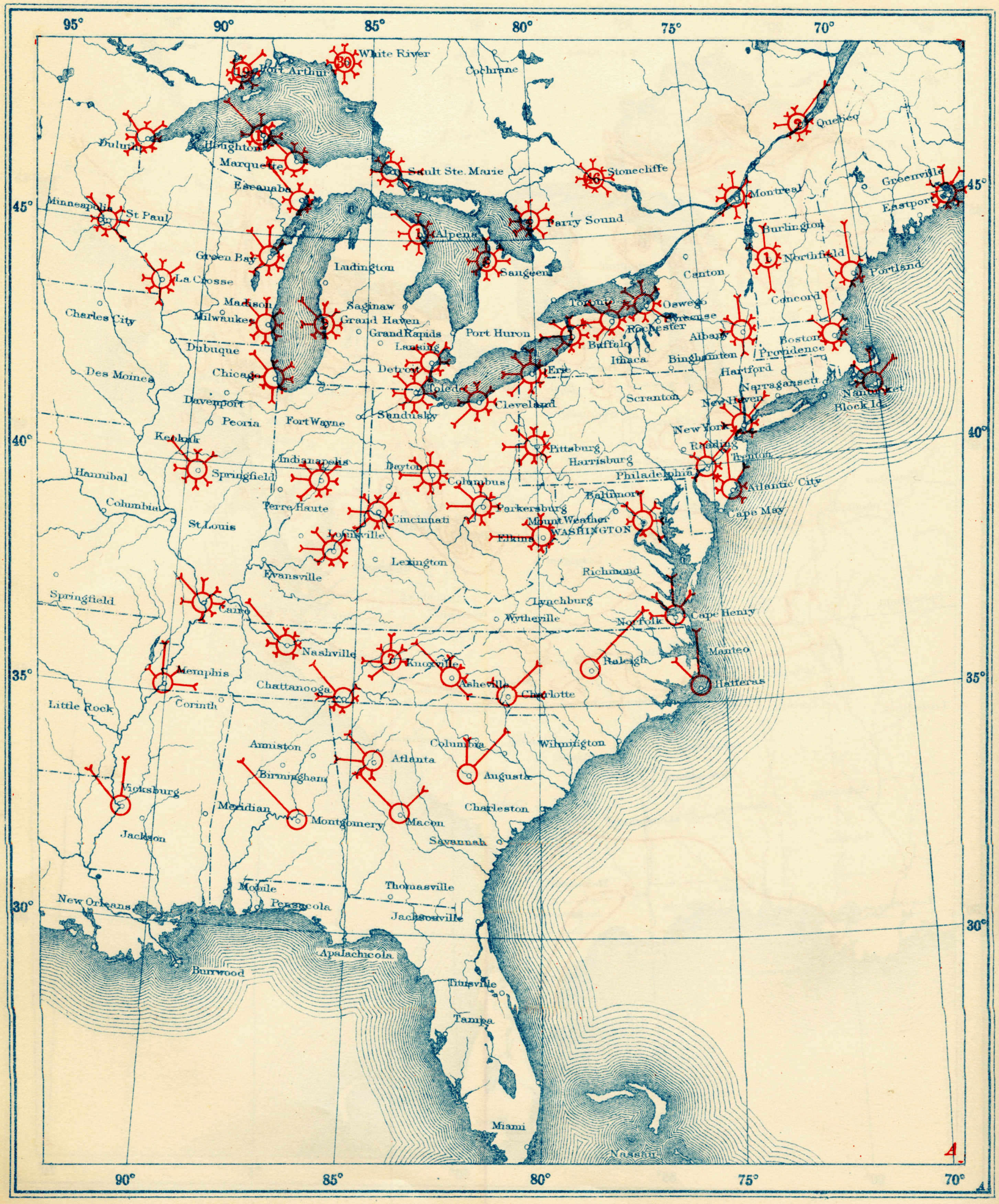
C. F. B. 2.—Average October snowfall (inches) over the eastern United States.



C. F. B. 3.—Average November snowfall (inches) over the eastern United States.

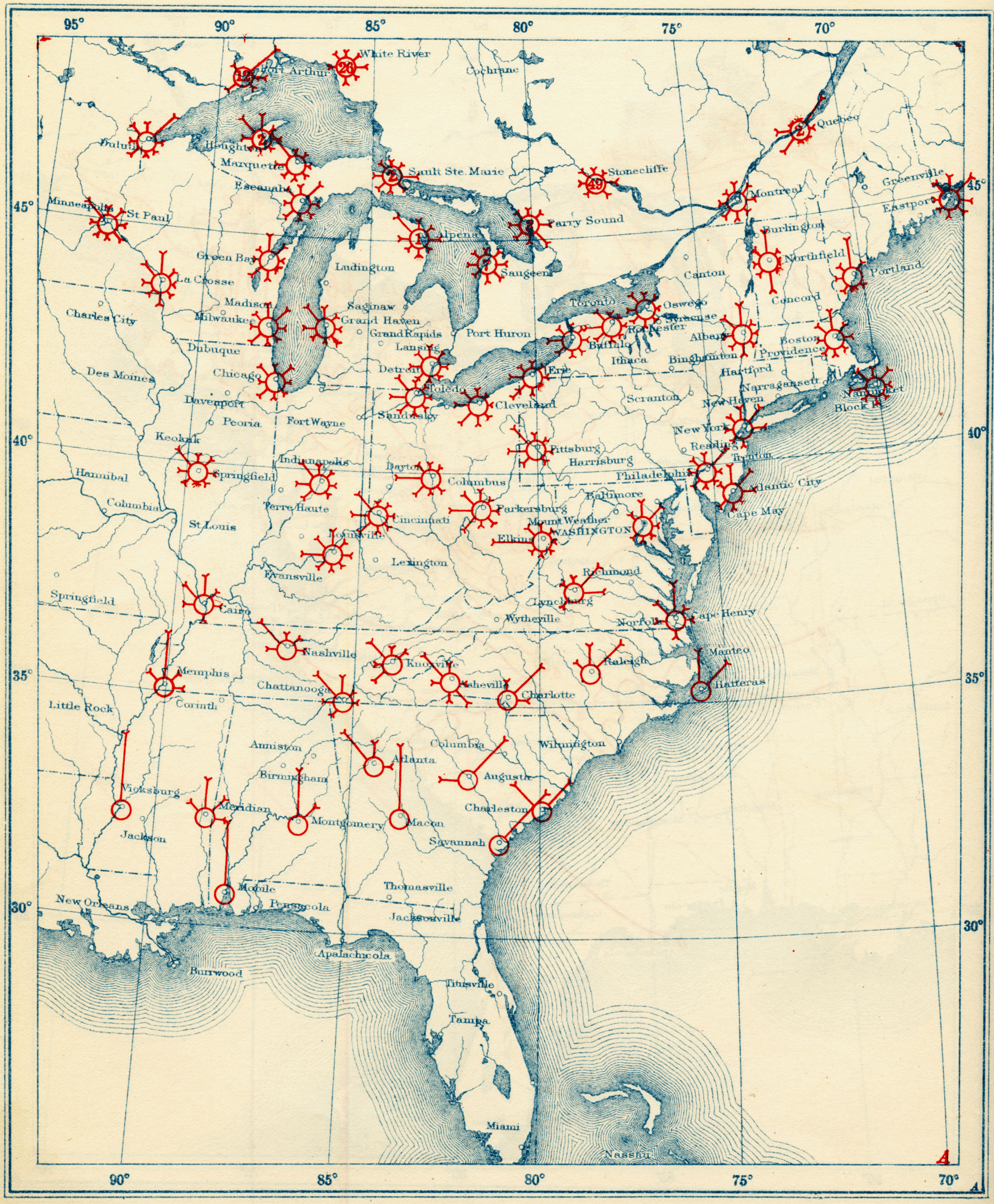
C. F. B. 4.—Snow-bearing winds in December over the eastern United States.

C. F. B. 5.—Average December snowfall (inches) over the eastern United States.

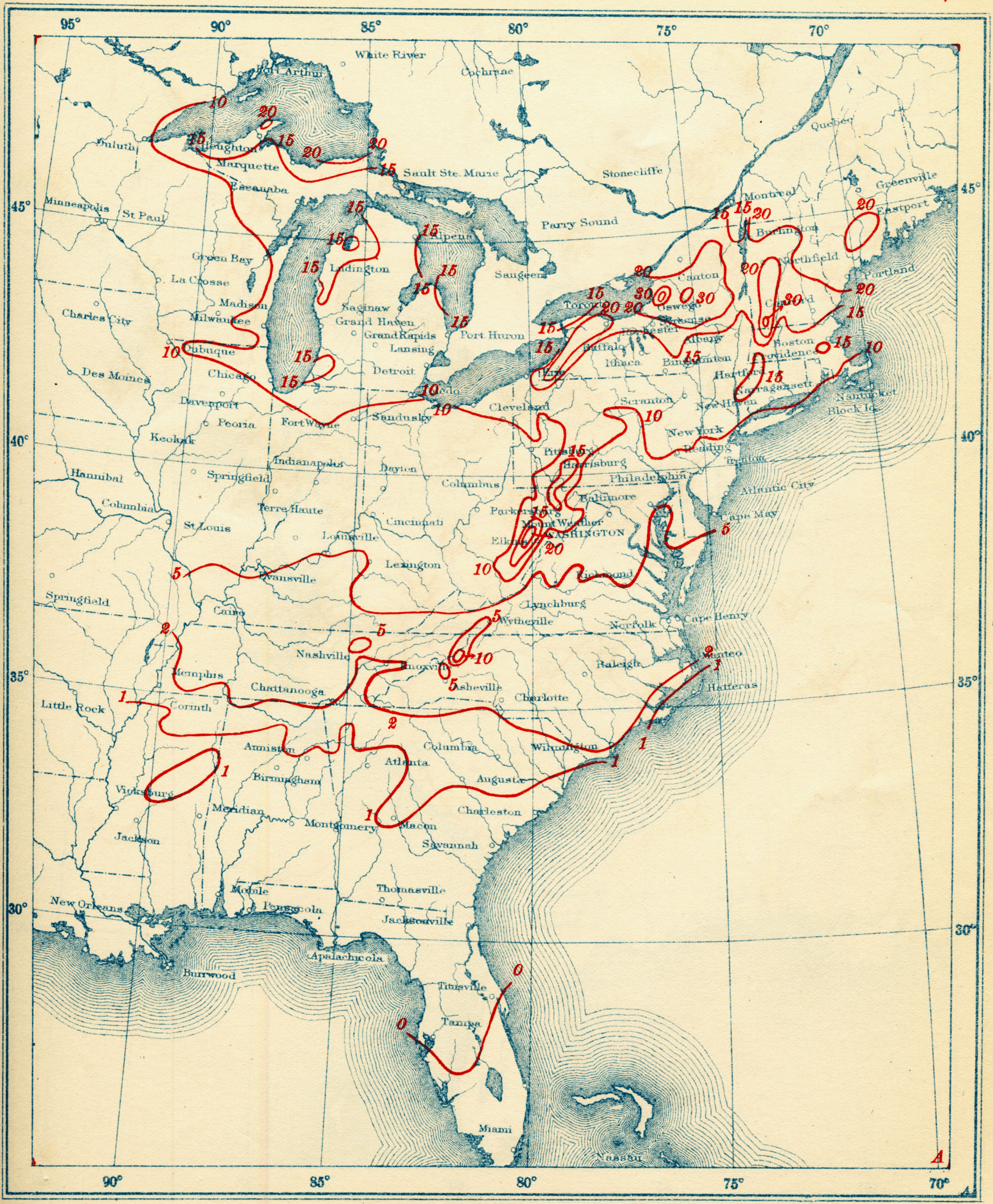


C. F. B. 6.—Snow-bearing winds in January over the eastern United States.

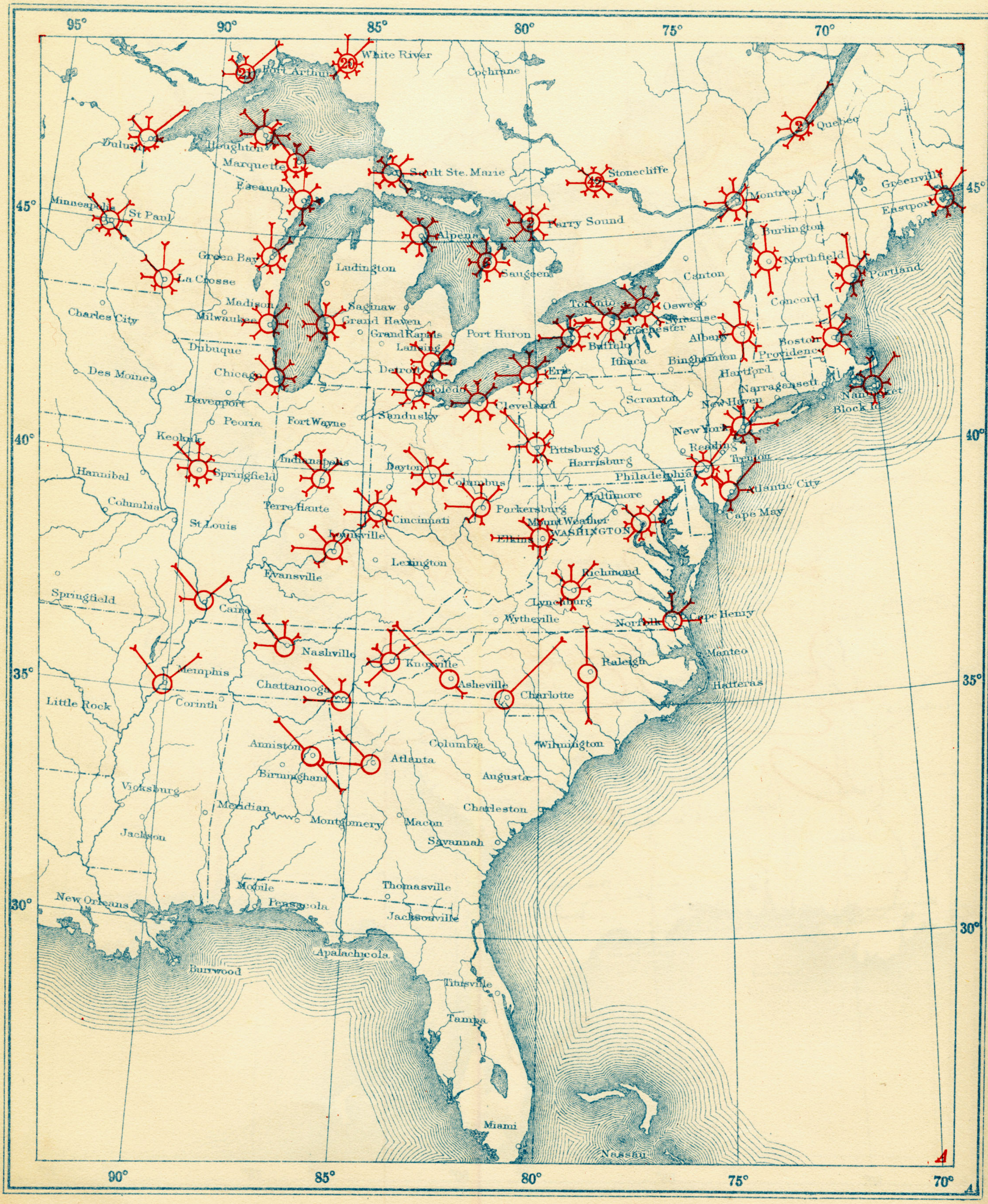
C. F. B. 7.—Average January snowfall (inches) over the eastern United States.



C. F. B. 8.—Snow-bearing winds in February over the eastern United States.



C. F. B. 9.—Average February snowfall (inches) over the eastern United States.

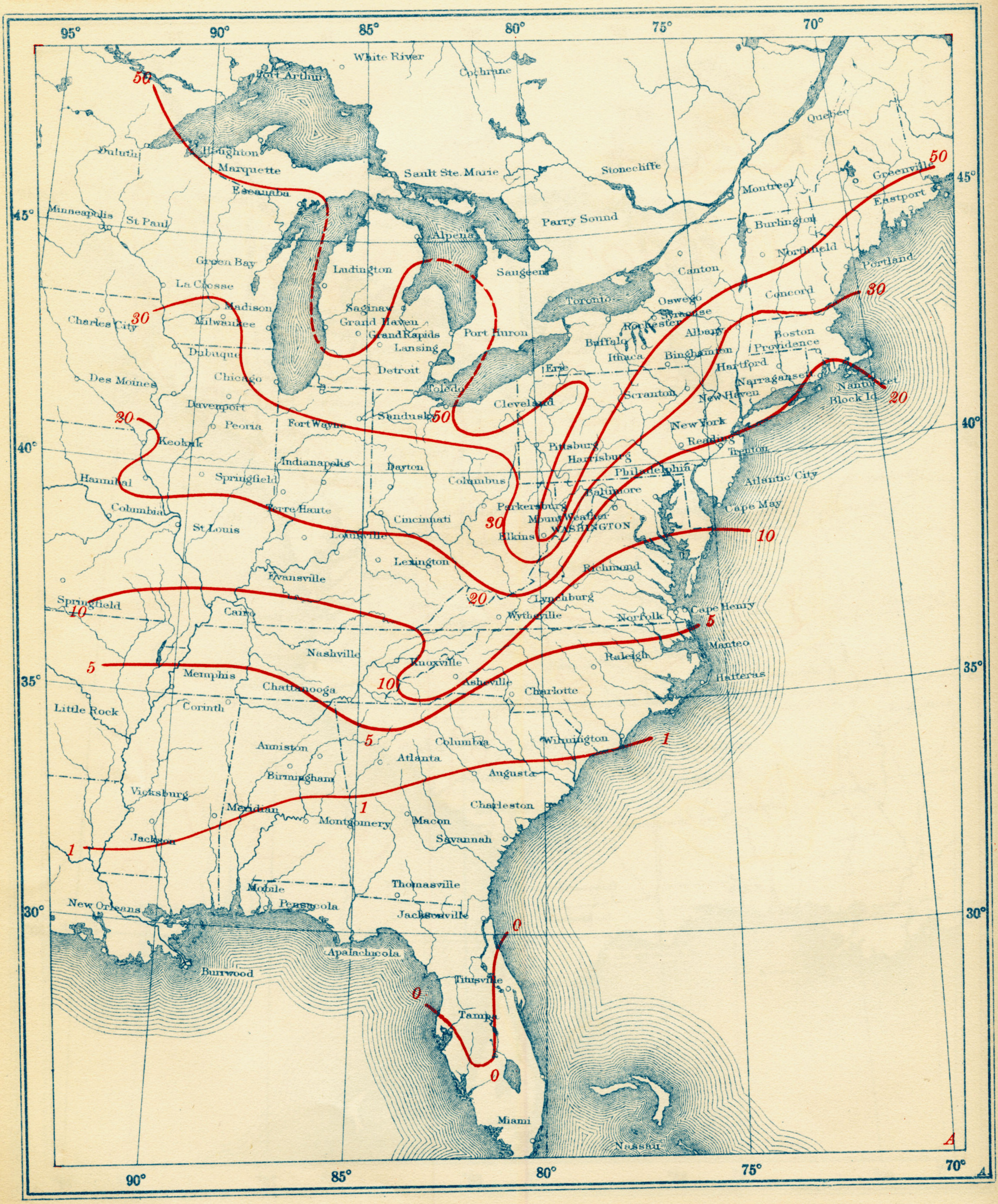


C. F. B. 10.—Snow-bearing winds in March over the eastern United States.

C. F. B. 11.—Average March snowfall (inches) over the eastern United States.

C. F. B. 12.—Average April snowfall (inches) over the eastern United States.

C. F. B. 13.—Average May snowfall (inches) over the eastern United States.



C. F. B. 14.—Average annual number of snowfall (inches) days in the eastern United States.

C. F. B. 15.—Average annual snowfall (inches) over the eastern United States (1895–1913).